The COsmic-ray Soil Moisture Observing System (COSMOS): a non-invasive, intermediate scale soil moisture measurement network

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Abstract

Soil moisture at a horizontal scale of around 700 m and depths of 15 to 70 cm can be inferred from measurements of cosmic-ray neutrons that are generated within soil, moderated mainly by the hydrogen atoms in water, and emitted back to the atmosphere. The intensity of the resulting field of neutrons above the ground is sensitive to water content changes, largely insensitive to soil chemistry and inversely correlated with hydrogen content of the soil. Measurement of this intensity with a portable neutron detector placed above the ground takes minutes to hours, permitting high-resolution, long-term monitoring of undisturbed soil moisture. The large footprint makes the method suitable for weather and short-term climate forecast initialization and satellite validation, while the measurement depth makes the probe ideal for studying plant/soil/atmosphere interactions. The intensity of cosmic-ray neutrons is also sensitive to water above the ground in snow, vegetation, or intercepted water, this water being in principle distinguishable from soil moisture. Instruments using this method are being deployed in the COsmic-ray Soil Moisture Observing System (COSMOS), which comprises initially a network of 50 probes (to provide a proof of concept) and subsequently 500 probes distributed across the contiguous USA. Additional COSMOS probes are also now being deployed on an experimental basis in the UK, Australia, and China.

Introduction

The fact that water re-evaporates from land surfaces back into the atmosphere to affect the weather and climate of terrestrial surfaces downwind has been recognized for decades. Early analysis of the global water budget (e.g. Baumgartner and Reichel, 1975) showed that on average over continental surfaces about 40% of terrestrial precipitation leaves as runoff, implying that the remaining 60% returns to the atmosphere by evaporation, contributing to precipitation downwind. Similarly, early studies of the isotropic content of water (e.g. Salati *et al*., 1979) were able to show that substantial proportions of measured rainfall originated from the terrestrial sources rather than all from oceanic sources.

When the first General Circulation Model (GCM) study to investigate the effect of land surfaces on climate (Shukla and Mintz, 1982) was made, it clearly demonstrated the need to include representation of terrestrial evaporation. More recently, the advent of reanalysis data derived from global meteorological models has allowed analyses (e.g. Brubaker *et al*., 1993; Eltahir *et al*., 1996; Costa and Foley, 1999; Bosilovich *et al*., 2005; Dominguez *et al*., 2008a) which quantify the magnitude in space and time of moisture recycled over land and track the origin of the recycled water falling as precipitation (e.g. Dominguez *et al*., 2008b).

As well as influencing the amount of water in the atmosphere for precipitation, the availability of soil moisture from evapotranspiration influences atmospheric processes by modifying the vertical structure of the atmosphere in regions downwind, and in this way changing the probability of rainfall. This is evident in analyses of hydrometeorological records (e.g. Findell & Eltahir, 1997), and it was dramatically demonstrated in the enhanced skill with which the major Mississippi floods in the summer of 1993 were predicted when improved representation of soil moisture status was introduced into the European Center for Medium-term Weather Forecasting model (e.g. Beljaars *et al*., 1996). Internationally coordinated GCM studies involving several models have since better determined regions where soil moisture control is most important (GLACE; Koster *et al*., 2006), although other studies also show that currently there are shortcomings in the quality of the representation of soil moisture evolution in GCM models (Teuling *et al*., 2006). There is also modelling and some observational evidence that transient soil moisture heterogeneity can influence mesoscale atmospheric circulations and hence the likely location of future rain (e.g. Taylor *et al*., 1997).

Area-average soil moisture measurements at the scale useful for atmospheric and hydro-ecological applications are, however, difficult to make. Up-scaling of point measurements of soil moisture is technically possible (Famiglietti *et al*., 1999, 2008), but it is difficult and costly (Western *et al*., 2002) due to the inherent small-scale heterogeneities of soils. Large-scale satellite remote sensing methods have other limitations (Entekhabi *et al*., 2004), including shallow measurement depth, limited capability to penetrate vegetation or snow, inability to measure soil ice, sensitivity to surface roughness, discontinuous temporal coverage, and the short life span of satellite missions. However, a recent breakthrough in understanding (Zreda *et al*., 2008) has resulted in the capability to make non-invasive reliable measurements of area-average soil moisture over hectares from the intensity of low-energy cosmic-ray neutrons

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measured using low power probes mounted a few metres above the ground. Using remote data capture and sensor management, such probes can be left to operate without local intervention. This paper overviews the basis for this novel method for measuring area-average soil moisture and the COsmic-ray Soil Moisture Observing System (COSMOS) project, which will install and operate an exploratory network of such probes over the next four years with potential for a ten-fold expansion in probe numbers thereafter.

Measuring soil moisture using cosmic rays

Neither the fundamental idea behind the measurement of area-average soil moisture using cosmic rays nor the basic sensor technology used is new. This is important from the standpoint of methodological readiness for large scale unsupervised deployment of the technique in a distributed network. Neutron detectors were first developed in the 1950s for use in cosmic ray science and in support of cold war activity. Consequently, they are now simple, robust and stable, and available off the shelf. The fact that surface moisture can alter the measured above-ground neutron count rate was also known in the 1960s and was in fact considered a nuisance in basic cosmic ray science. Figure 1 shows the result of an early study of how measured cosmic ray intensity alters above the ground and with the moisture of the underlying surface (Hendrick and Edge, 1966).

What is new is systematic understanding of cosmic-ray neutron interactions at the ground-atmosphere interface based on measurements and modelling. Studies have identified that the above-ground ‘*fast*’ (~1 MeV) neutron density that results from cosmic rays interacting with soil:

(a) changes slowly with height above the ground;
(b) is related to area-average moisture content over a source footprint of hectometers and a depth of 70 cm for dry soil and 12 cm for wet soil; and
(c) has limited sensitivity to soil type.

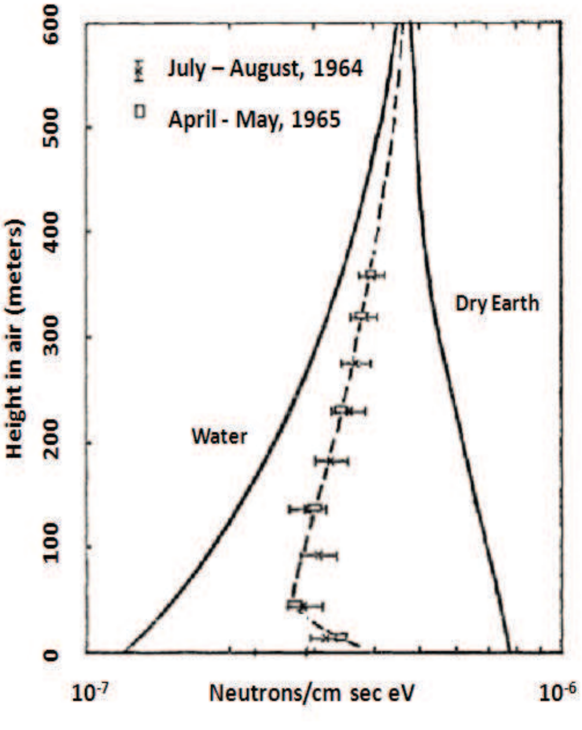


Figure 1 *Measured variation in cosmic ray intensity with height above the ground and moisture of the underlying surface (redrawn from Hendrick and Edge, 1966).*

This understanding, together with better (solar) power systems and the ready availability of high quality, low power electronics for pulse shaping and amplification and for remote detection and correction of sensor drift and remote data capture, have resulted in the commercial availability of the ‘COSMOS probe’.

How does the COSMOS probe work? Clearly the process starts in space where there are incoming, very high energy cosmic ray protons. These are captured by the Earth’s magnetic field and enter the top of the atmosphere, see Figure 2a. The overall rate at which cosmic ray protons arrive depends on astronomic processes and changes (by a few percent) slowly with time. This slow change in overall cosmic ray intensity is directly reflected in proportional changes in the count rate measured by all COSMOS probes near the ground and so has to be corrected for. This is done by including an accurate cosmic ray monitor mounted at high altitude within the COSMOS system to monitor the gradual change in cosmic ray intensity. The rate at which cosmic rays enter the atmosphere also changes in response to geomagnetic influences because the protons, being charged, interact with the Earth’s magnetic field. The resulting spatial pattern in the intensity of incoming protons entering the atmosphere (which changes as the Earth’s magnetic field changes) also has to be corrected for in the COSMOS system, but fortunately this pattern is well understood, see Figure 2b.

In the atmosphere, the incoming protons generate cascades of secondary cosmic rays (Figure 2c) and the intensity of these cascades at the ground depends on how much mass was encountered during the transit through the overlying atmosphere, i.e. it varies with surface air pressure and, to a lesser extent, with temperature. The effect of changing pressure and temperature in response to the altitude of the probe and changing meteorological conditions therefore also has to be corrected for, so the COSMOS probe includes pressure and temperature sensors. Once in the soil, the cosmic cascade encounters much denser mass and many neutrons are created which are then scattered and lose energy (‘thermalized’) and are absorbed by the moist soil, see Figure 2d. Most neutrons are absorbed in the soil but some escape back into the air. The density of the field of neutrons so created above the ground depends on the composition of the soil and, in the case of ‘fast’ neutrons, especially on the water content (strictly hydrogen content) of the soil because hydrogen is by far the most effective element in ‘thermalizing’ and absorbing fast neutrons, see Figure 2e and 2f. The COSMOS probe exploits this fact. It is by measuring the intensity of the field of neutrons from the observed count rate in a detector that senses only fast neutrons that soil moisture is determined.

In practice, because air is much less dense than soil, the intensity of the field of fast neutrons changes slowly with height (by ~1% over 20 m) above the ground, so the height at which the COSMOS probe is mounted is not critical. The low density of air relative to soil is also the fundamental reason why the COSMOS probe can sample soil moisture over a large footprint. It means that once fast neutrons have escaped from the soil surface, they can travel large distances so the density of the neutron field measured by the detector at a particular point is in part determined by the neutrons that were originally released from the soil a considerable distance away.

How is the COSMOS probe calibrated? In practice, this is greatly simplified by the fact that it is the water (strictly hydrogen) content of soil and not its chemical content that has overwhelming influence on the density of the field of fast neutrons measured above the surface. The relationship between neutron intensity and soil water content cannot

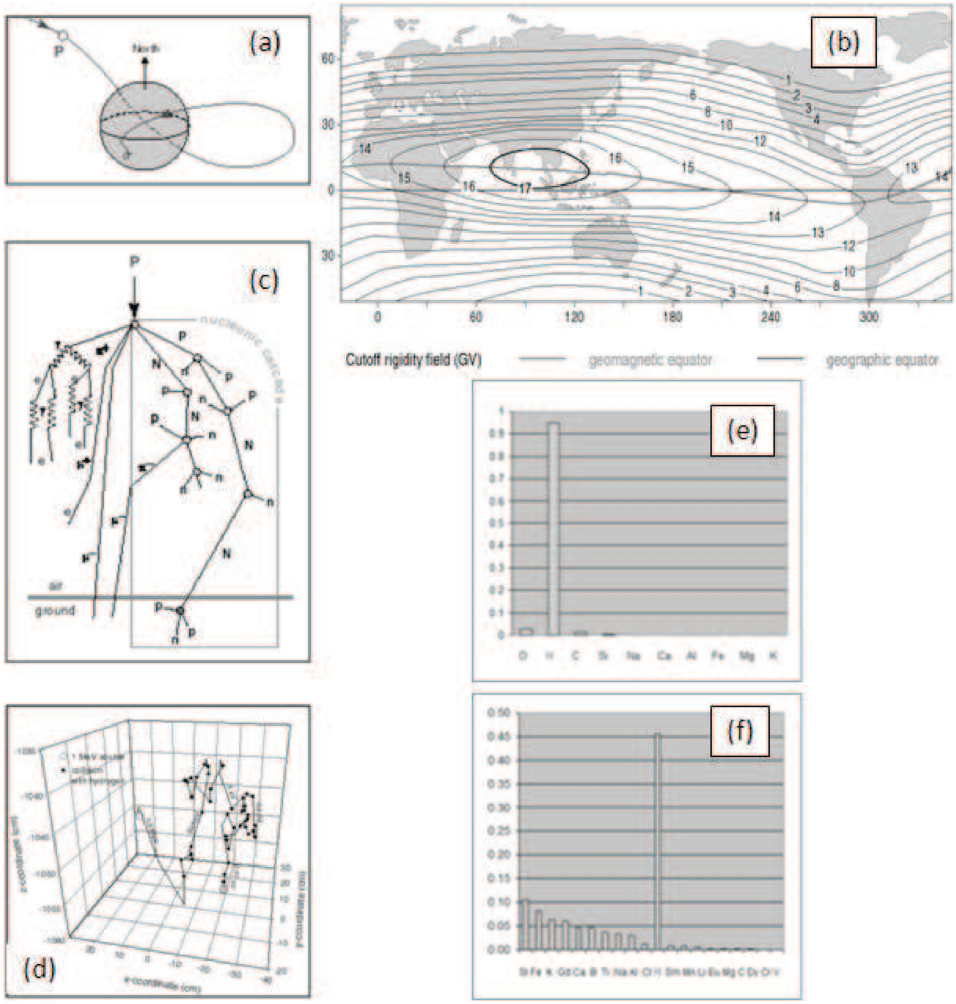


Figure 2 *Important facets of the processes involved in the measurement of soil moisture using cosmic rays:*
(a) high energy cosmic ray protons are captured by the Earth's magnetic field at a rate the percentage change in which is monitored by the COSMOS network;
(b) the protons enter the top of the atmosphere with a well understood spatial distribution which is related to the slowly changing magnetic field of the Earth;
(c) cascades of cosmic particles are produced in the atmosphere at a rate determined by the pressure and temperature of the atmosphere;
(d) the cosmic showers enter the soil to generate a spectrum of neutrons which are ultimately "thermalized" and captured at a rate that is primarily determined by the hydrogen content of the soil. This is because hydrogen is relatively the most effective soil constituent at slowing, see
(e), and absorbing, see (f) neutrons. Some neutrons leak back into the atmosphere, however, to give a density profile which varies with the moisture content of the soil, see, for example, Figure 1.

be determined analytically, but it can be investigated using (albeit computationally expensive) '*Monte Carlo*' simulations which track the movement and location of individual neutrons generated for prescribed profiles of soil water chemistry, including water content. In this way, the intensity of neutrons with different energies can be simulated within the soil and above the ground. Figures 3a and 3b are representations of a Monte Carlo simulation of neutron density made in this way for different area-average soil moisture conditions. Figures 3c and 3d show the relationships between the intensity of neutrons (as reflected in the flux of neutrons through a detector) for 'thermal' and 'fast' neutrons determined by such simulations, respectively, calculated for a range of soil types and for different soil moisture content.

The result of such modelling studies for fast neutrons is extremely important in the context of the COSMOS probe because it shows that the shape of (the non-linear) relationship between soil moisture content and fast neutron count rate is largely insensitive to the nature of the soil, albeit that the offset in the relationship has some small sensitivity to soil chemistry. This means that the COSMOS probe count rate for fast neutrons has to be calibrated just once (usually at installation) against alternative (usually gravimetric) soil moisture measurements to determine the offset because its value is insensitive to the value of soil moisture during calibration. The calibration for thermal neutrons is, however, much more complex and the inclusion of a second detector for thermal neutrons in the COSMOS probes is *not* for soil moisture detection, rather it is to allow possible determination of water stored on the surface of the soil, as snow and ice for example. But the physical basis for such a measurement is not fully understood at this writing, and further research is needed to enable this application to be realized.

The results of Monte Carlo calculations in which knowledge of the origin of the fast neutrons reaching a specified detector position is retained can be used to define the sampling volume of the COSMOS probe. Figures 4a and 4b show the result of such calculations. The effective sampling depth of the probe varies substantially with soil moisture content (as might be expected), with 86% of

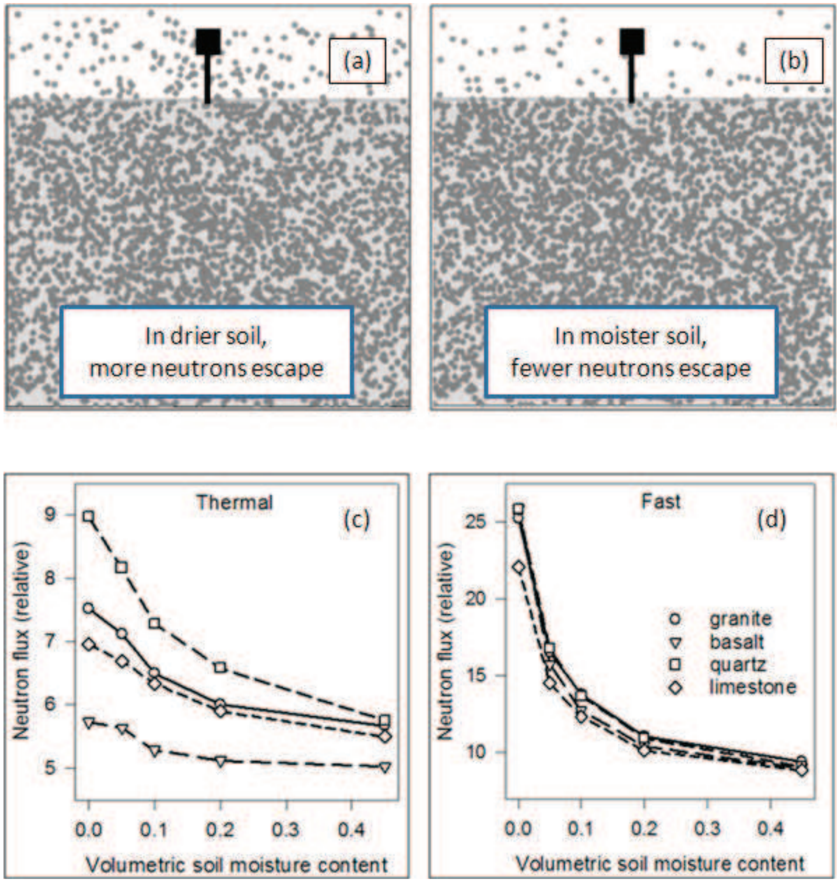


Figure 3 *(a) and (b) representations of a Monte Carlo simulation of neutron density made for dry and moist area-average soil moisture conditions, respectively. (c) and (d) the relationships between the intensity of neutrons measured above the ground for "thermal" and "fast" neutrons, respectively, as determined by Monte Carlo calculations for a range of soil types and for different soil moisture content.*

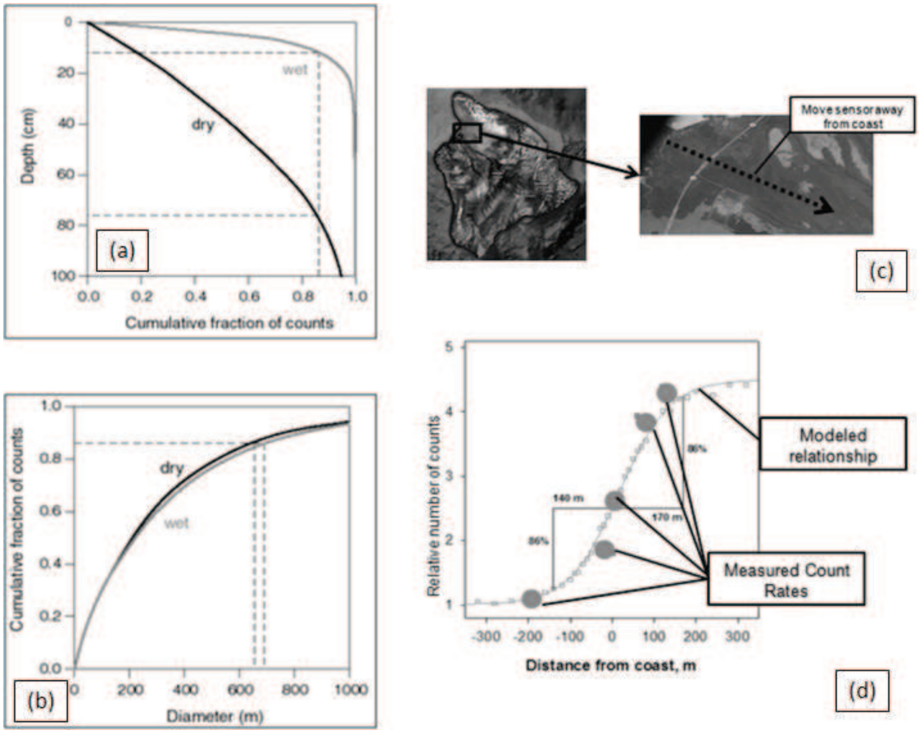


Figure 4 *(a) Monte Carlo calculations in dry and wet soil conditions of (a) the effective sampling depth and (b) horizontal footprint of the COSMOS probe. Experimental check of the footprint of the COSMOS probe made at the site in Hawaii shown in (c) where the coastline interfaces with a non-vegetated basalt flow. A probe initially over the ocean was moved progressively larger distances inland and the count rate measured. (d) Comparison between change in measured count rate with distance from the coast and calculated change in rate given by Monte Carlo simulation.*

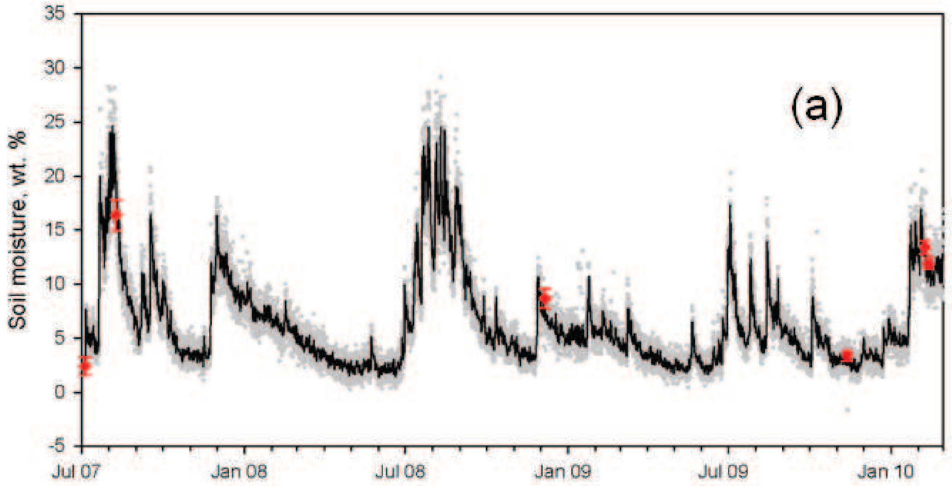
measured neutrons originating from within a depth of around 70 cm for dry soils, and from within a depth of around 12 cm in wet soils, these values being independent of the altitude of the probe (i.e. independent of air pressure). The radius within which neutrons are sampled is largely independent of soil moisture because it is mainly determined by the distance fast neutrons can travel in the air so does increase with altitude (and reduced air pressure). For typical air pressures, about 86% of neutrons originate within a radius of about 350 m. These specifications of source volume are determined from modelling studies, but an approximate check on the size of the foot print has been made at a site in Hawaii where the coastline interfaces with a non-vegetated basalt flow. A COSMOS probe initially over the ocean was moved progressively larger distances inland and the count rate measured, see Figure 4c. The comparison between the change in measured count rates with distance from the coast in the this experiment and the change in count rate calculated by Monte Carlo simulations is reassuring, see Figure 4d.

Figure 5a shows the results of a study made in the San Pedro river basin between January 2007 and February 2010 in which the measured area-average soil moisture given by a COSMOS probe was compared with measurements made by gravimetric sampling. The first sample was used to provide the calibration offset for the COSMOS probe so its consistency with the COSMOS probe value is not significant, but the fact that the several subsequent gravimetric samples are numerically consistent with the COSMOS probe measurement is very significant and demonstrates the consistency of the probe calibration.

The procedure used to make a one-time calibration of a COSMOS probe (usually at installation) merits further discussion. Figure 5b shows the estimated sampling error in an average gravimetric calibration based on an increasing number of samples taken in a typically heterogeneous soil moisture field. The statistical counting error in an hour long measurement of area-average soil moisture made with a COSMOS probe is about 2% (Note: this counting error can easily be reduced to 1% if a four-hour long measurement is made). As Figure 5b shows, to achieve a comparable statistical error of 2% using gravimetric sampling requires about 30 to 40 point samples. In practice, the standard procedure used in the one-time calibration of the COSMOS probe involves taking gravimetric samples soil at three depths, in eight directions, and at three radii around the probe, i.e. 72 soil samples.

The COSMOS Project

Funding for the COSMOS project was approved by NSF for four years from September 2009 to August 2013. The project is operating in “proof of concept and demonstration of data utility mode”, with opportunity for a tenfold expansion of the number of probes in the US national network thereafter, subject to success in this initial phase. Fifty COSMOS probes will be deployed in the first two years of the project at sites selected to provide maximum benefit to the scientific community, and to demonstrate the value of this new soil moisture measuring method effectively. To aid definition



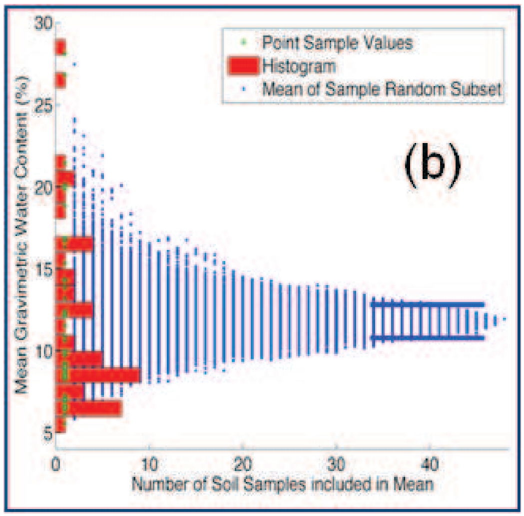


Figure 5

(a) Results of a comparison study made in the San Pedro river basin between January 2007 and February 2010 in which the measured area-average soil moisture given by a COSMOS probe was compared with equivalent measurements made by gravimetric sampling. Grey points are hourly estimates of soil moisture from the COSMOS probe, the black line is a 7 hour running average of these values, and the red points are gravimetric measurements based on 72 soil samples with error estimate.

(b) Estimated sampling error in an average gravimetric calibration based on an increasing number of samples taken in a typically heterogeneous soil moisture field.

of preferred sites for probe deployment, COSMOS held a workshop at the American Geophysical Union Fall Meeting in December 2009 at which advice was sought from the approximately 70 multi-disciplinary scientists attending the workshop. Participants included scientists active in the AMERIFLUX (http://public.ornl.gov/ameriflux), NEON (http://www.neoninc.org/), CUAHSI/CZO (http://www.cuahsi.org/), SMAP (http://smap.jpl.nasa.gov/), and SMOS (http://www.smos.esa.int/) communities.

The recommendations of the COSMOS workshop were as follows:

- make deployments that support scientists in all three NSF programs providing COSMOS funding (i.e., NSF's Atmospheric Science, Biology, and Hydrology Programs);
- deploy probes only at sites where there is ongoing, publicly available relevant ancillary data collection that includes at least surface meteorology and energy flux measurements;
- link deployments to existing networks whenever possible; and
- give some priority to sites in the center of the US where previous studies (e.g., Koster et al, 2006) suggest seasonal climate forecasts are most sensitive to soil moisture status.

Consistent with these recommendations, the primary goals of the COSMOS project over the next four years are:

(a) to improve understanding of soil moisture controls in weather and climate models and of ecological processes and phenomena and hydrological flow processes in catchments;
(b) to investigate the ability to measure water storage on/in vegetation canopies and as frozen precipitation using cosmic ray techniques, and to calibrate and/or validate remotely sensed measurements of soil moisture.

In pursuit of these goals, the current plan for COSMOS deployment sites during 2010 are shown in Figure 6a. The potential US COSMOS network if collated with existing monitoring networks during a potential large scale deployment starting in four years is shown in Figure 6b. To achieve the goal of providing calibration and/or validation of remotely sensed measurements of soil moisture, it will be necessary to redevelop the existing probe to make it more efficient by increasing the net count rate of the sensor and also by making it more mobile by mounting it on a moving platform (most likely a truck or 'all terrain vehicle'). To allow soil moisture measurements with an accuracy of around 2%

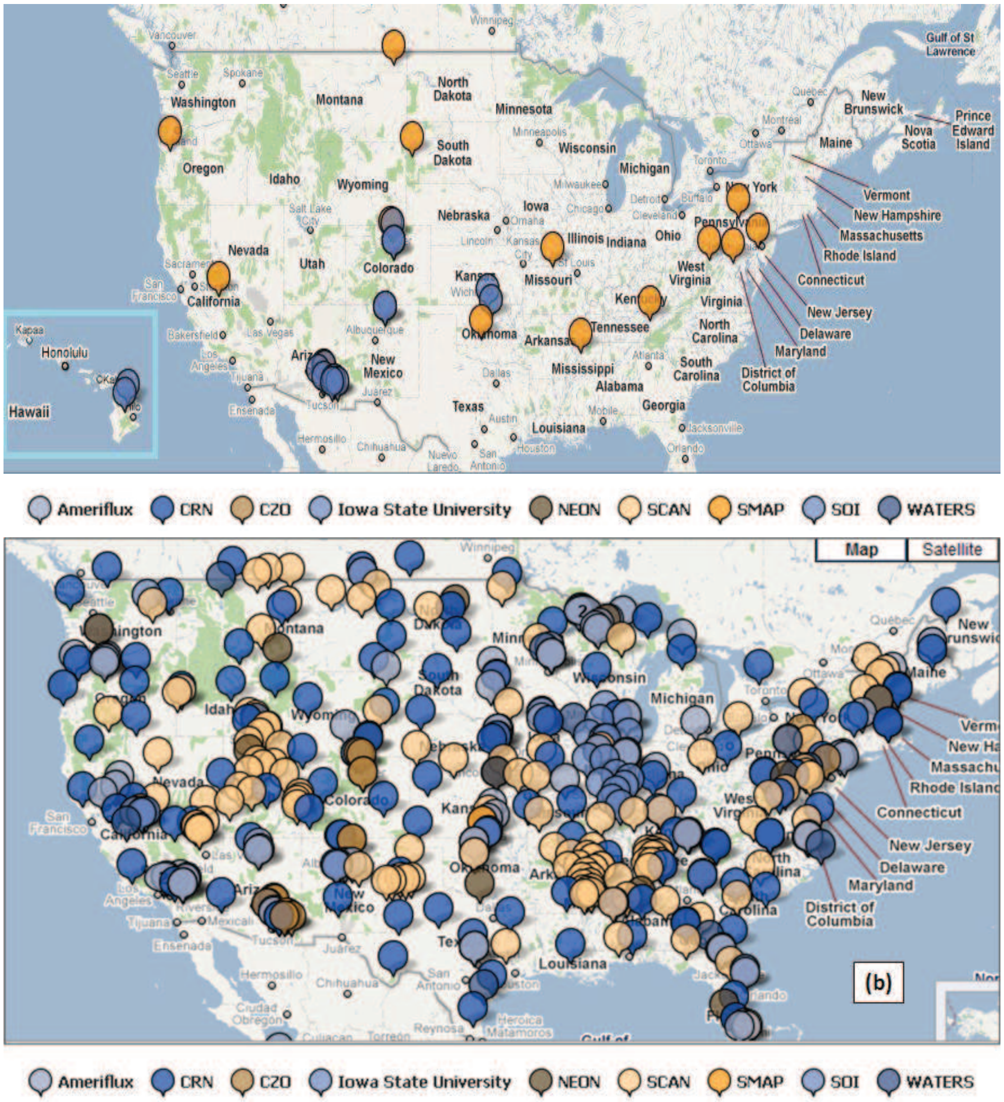


Figure 6 *(a) Currently planned COSMOS deployment sites during 2010 (provisional). (b) a potential US COSMOS deployment network if COSMOS sites are collated with existing monitoring networks during a subsequent large scale deployment starting in four years time.*

over a sampling area comparable with that of the SMOS or SMAP satellite using a cosmic ray probe mounted on a moving platform, it is estimated that it will be necessary that the platform has a driving speed of less than 12 km hr^{-1}, and for the probe to have a net sampling volume approximately 16 times that of the current COSMOS probe. This could be achieved by mounting four probes, each with a sampling volume four times bigger than the current probe, side by side and summing the total count rate. These probes would have the same electronic hardware as the current probe but the system would also require a global positioning system and associated firmware to record the probe's position. Ideally this mobile COSMOS probe would be deployed where there are also fixed COSMOS probes in the satellite footprint. Soil moisture maps could then be derived from a combination of the roving and fixed probes count rates using time-for-depth data assimilation methods to derive near surface soil-moisture at the fixed probe sites, and then sequential kriging to spatially interpolate the roving and fixed probe data to derive an estimate of near surface soil moisture over an area comparable to that measured by the satellite system.

Summary and Conclusion

The need for area-average soil moisture (and other surface moisture) measurements to improve understanding of atmospheric, hydrological and ecological processes is now irrefutable. This paper draws the attention of the scientific community to the fact that a proven technique exists for measuring soil moisture to a depth of around 70 cm and over a circle radius around 350 m based on measuring high energy neutron count rates a few metres above the surface, using an off the shelf device that is self powered and has remote data capture, and that can be installed in two days with a single field calibration. Extension of the cosmic ray measurement concept into the role of providing calibration and/or validation of satellite soil moisture data is also under investigation

Fifty COSMOS probe devices will be deployed at carefully selected sites across the USA in the next two years and the data from these will be made freely and publicly available along with associated meteorological and surface flux data via the internet in near real time. The opportunity subsequently to extend this network to 500 probes nationwide depends on the scientific community's enthusiasm to use these data and to demonstrate their value for improving scientific understanding and hydrometeorological prediction.

Acknowledgement

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